Simulating Water Quality in the Duwamish Estuary and Elliott Bay: Comparing Effects of CSOs and "Other Sources"

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Introduction

King County owns and maintains the wastewater treatment plants and the large conveyance pipes that carry the wastewater for Seattle and most of the smaller cites within the county boundaries. In parts of the conveyance system, the system is connected to both sewage and stormwater lines in what is termed a combined system. During periods of dry weather the conveyance system transports mainly sewage to the treatment plants. When the county experiences a significant rainfall event, the capacity of the conveyance system is exceeded thus forcing combined sewage and storm water to overflow into the local water bodies surrounding Seattle. These sites are termed combined sewer overflows (CSO). CSOs only discharge when the ability of the conveyance system to transport sewage is exceeded due to the rainfall event. Currently the largest number of CSOs are in the Duwamish Estuary; hence the focus of this study is in the estuary (See Figure 1).

Figure 1. WQA study area

The Department of Ecology (DOE) requires the county to keep records on the number of discharges, volume of overflow, and chemical content of CSOs as part of the National Pollution Discharge Elimination System (NPDES). King County made agreements with DOE to reduce the number of CSO discharges from all sources to one untreated event per year, without a specific deadline for achievement of this standard. Federal standards allow four to six untreated discharges per year.

As part of the county's commitment to maintain or improve water quality, it embarked on the task to determine how significant CSO discharges into the Duwamish Estuary are compared to other contaminant sources that discharge into the estuary as well. The project, called the Water Quality Assessment (WQA), looks at the risk to human health and aquatic life as it exists today and what it would be without CSOs discharging into the estuary. To assess risk, the county is using chemical concentrations in the water, sediments, and aquatic life (primarily fish). Values for the water and sediment chemical concentrations will be obtained from a computer model that has been calibrated against observed field data.

Chemicals of Potential Concern

Eutrophication is not a problem in the Duwamish Estuary and Elliott Bay. Sampling of dissolved oxygen (DO) revealed that DO concentrations were always above 7 mg/L, even during CSO events. Flow through the estuary is rapid enough such that no other eutrophication processes pose significant risk to aquatic life. The chemicals that are of potential concern (COPC) in the estuary and bay were selected based on availability of data, water and sediment standards, and those known to inpact the health of humans or aquatic life. The COPCs modeled in this risk assessment are:

- Metals: Arsenic (As), Cadmium (Cd), Copper (Cu), Lead (Pb), Nickel (Ni), Zinc (Zn), Mercury (Hg), Tributyltin (TNT);

- Organic compounds: 1,4 Dichlorobenzene, 4 Methylphenol, Bis(2 ethylhexyl)Phthalate, Fluoranthene, Phenanthrene, Total PCB, Pyrene, Benzo(k)Fluoranthene, Chrysene, Benzo(b)Fluoranthene;

- Fecal coliform bacteria.

Use of a computer model for the WQA study is twofold: 1) it will be used as a mass balancing tool to estimate chemical contributions from other sources given CSO, ambient, and boundary chemical loads, and 2) it will be used as a surrogate field sampling program. This paper discusses how the model was prepared and applied for the WQA risk assessment.

The Duwamish Estuary

The Duwamish Estuary is located in the heart of Seattle's industrial area southwest of downtown, and flows north into the southern tip of Elliott Bay. It is a heavily used shipping port and is a significant habitat area for salmon and other wildlife. The estuary is defined as the body of water starting from the mouth at Elliott Bay to 18.5 km upstream. Most of the estuary is dredged for shipping with dredging extending approximately 12.5 km upstream from the mouth. The mean river flow is about 42.5 cubic meters per second (cms) or 1500 cubic feet per second (cfs). The estuary is well stratified (salt-wedge type) when fresh-water inflow rates are greater than 28 cms (1,000 cfs); but when flows are less than 28 cms, the lower 5.5 km of the estuary grades into the partly mixed type. Cross-channel distribution is generally uniform for a given location and depth. Salinity migration is controlled by tides and freshwater flow. The upstream extent of the wedge is dependent upon fresh-water inflow and tide height and can range from 2–16 km upstream from the mouth. Dye studies indicate that downward vertical mixing over the length of the salt-wedge is almost non-existent.

Freshwater flow into the estuary comes from the Green River. The river is regulated at the Howard Hanson dam for flood control. However, flow rates do vary considerably day to day because of storm runoff and snow melt. Upstream tidal flow reversal has been observed in the Green River 21 km upstream of the mouth.

Water depth in the dredged sections of the estuary vary from 15 m at mean lower low water (MLLW) at the mouth to 3.6 m at 14th Ave bridge (9.5 km). The channel above the turning basin is not dredged and varies in depth from 1 to 2 meters (MLLW). Elliott Bay, at its deepest location, is about –150 m (MLLW). Tides in the Duwamish have ranged from –1.4 to +4.5 m from mean lower low water. Freshwater flow from the Duwamish discharges into Elliott Bay causing a freshwater lens atop the saline waters in the bay.

Modeling Objective

The objective of the modeling program was to use the computer model as a mass balancing tool to determine mass loading contributions from sources other than CSOs. The model was then used to assess the differences in resulting water and sediment concentrations due to CSOs and "other sources." These differences could then be used in a risk assessment process to quantify the risk to humans and aquatic life from CSOs relative to "other sources." Therefore, it was assumed that there are three basic chemical

sources in the estuary: boundaries, CSOs, and "other sources". King County had limited financial resources and limited its scope of work to collecting information on CSO chemical compounds and ambient chemical concentrations. Knowing two of the three sources, the computer model was employed as the third equation to estimate inputs from the other chemical sources.

Computer Model Description

King County selected the Environmental Fluids Dynamic Computer Code (EFDC) developed by Dr. John Hamrick for application to the WQA modeling. It was selected over other models because it can simulate highly stratified flows and both nutrients and toxic compounds. It has been applied to many estuarine studies, and it is non-proprietary. The county reviewed 13 different models for application to the Duwamish. They were rated against a set of requirements (defined by the county) that were based on the needs of the WQA and observed conditions within the estuary (See Walton, 1998).

EFDC is a curvilinear-orthogonal, three-dimensional hydrodynamic-chemical transport and fate model. The hydrodynamic and transport modules are coupled. The vertical dimension is transposed into a stretching coordinate system where cell layers move with the free surface. Hydrodynamics are solved using the depth integrated momentum equation and employs a turbulent-intensity and length-scale transport equation to solve for turbulent viscosity and diffusion. Transport and fate is solved using the mass transport equation and incorporates a near field model which can be coupled to the mass transport model. For a detailed explanation of the model derivation see Hamrick (1992).

The study area was segmented into 500 cells in the horizontal plane, and ten layers in the vertical for 5,000 cells in total. The EFCD model was modified to simulate near-field CSO effects within the larger model cells, and to simulate chemical fate equations as a function of the physical and chemical state of the estuary and bay.

Field Monitoring Program

Water velocity, elevation, temperature, and salinity were collected during the field-monitoring program. Acoustic doppler current meters were used to measure water velocity. Three meters were deployed in the estuary and two in Elliott Bay. The meters measured the horizontal and vertical components of the water velocity. Velocities were measured at half-meter intervals in the estuary and at 4-meter intervals in Elliott Bay. Salinity, temperature, and water elevations were measured at three field stations in the estuary. Two stations had two instruments placed one meter below the surface and one meter above the bottom. The third station had a single instrument placed one meter below the surface.

To determine the feasibility of an intense field sampling program, King County did a pilot study to see if it was possible to collect the number of samples required and if current laboratory analytical techniques were appropriate. The pilot study revealed that most of the organic compounds were non-detects and the saline water of the estuary significantly interfered with measuring metals. The County instigated new laboratory procedures to remove the saline matrix from the water samples, also lowering the detection limit by an order of magnitude. To overcome the inability to measure organic compounds using conventional laboratory procedures, Semi-Permeable Membrane Devices (SPMD) were used. The SPMDs were deployed for two weeks and provide a time-averaged estimate of water concentrations over the deployment period. Organics were still sampled using conventional methods approximately once per month and except for bis(2-ethylhexyl)phthalate, all other organic COPCs were non-detects.

The field-monitoring program was started October 31, 1996 and ended June 4, 1997. Approximately 26 sampling trips where performed during this time period. Samples were taken either once or three times per week. If the three largest CSOs were not discharging (non-storm event), one sample was collected for that week. If the three CSOs were discharging (storm event), then sampling occurred over three consecutive days. Personnel were put on 24-hour alert, seven days a week, to mobilize for storm sampling. For safety reasons, it was decided that sampling would only occur during daylight hours. Because of this, some storm sampling trips did not commence until the tail end of the storm period when CSOs had slowed considerably.

Sampling locations were selected along the length and width of the estuary, see Figure 2. Samples were taken one meter below the surface and one meter above the bottom at most river sites. Samples were taken 15 to 20 m below the surface in Elliott Bay. Samples were taken at three locations across the river at most of the river sites. The parameters measured are listed in Table 1.
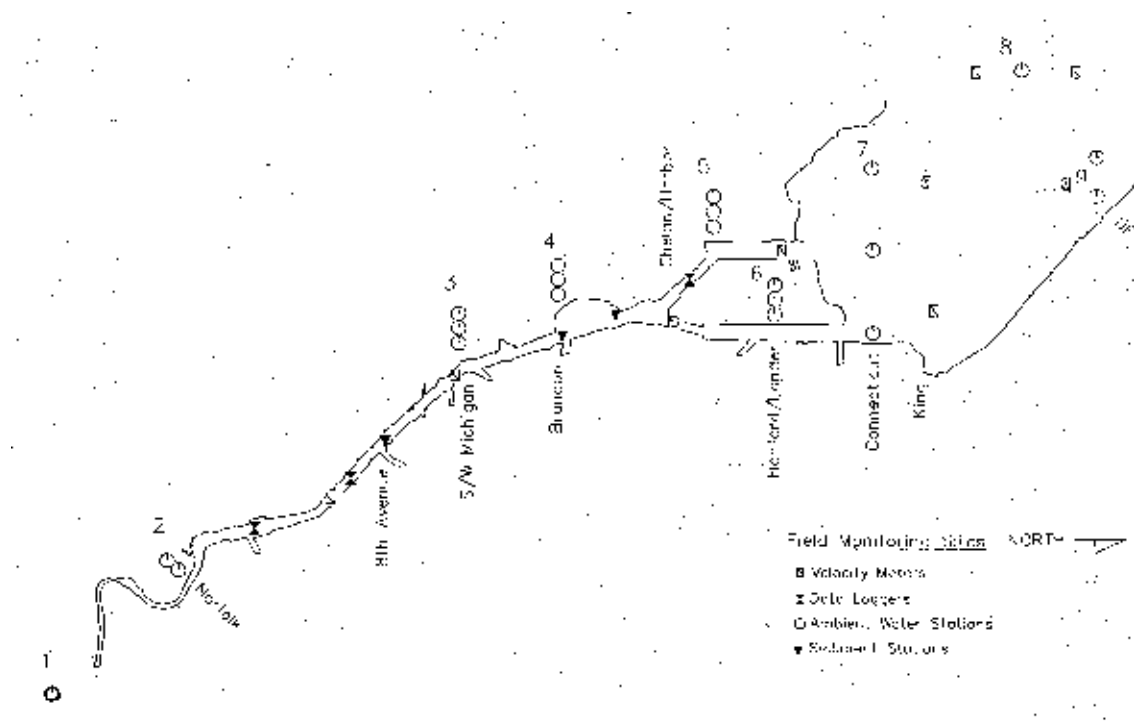

Figure 2. Locations of sampling and field instrument sites.

Table 1. Quantities measured for COPCs.

Chemical of Concern	Measuring Technique	Measured Quality	
		Water	Sediments
Metals: As, Cd, Cu, Pb, Ni, Zn	Standard Analytical Methods (SAM)	T,D	T,TOC,TS
Organic:			
1,4-Dichlorobenzene,	SAM	T,D,TVS	T, TOC,TS
4- Methylphenol,	SAM	T,D,TVS	T, TOC,TS
Bis(2-ethylhexyl)Phthalate,	SAM	T,D,TVS	T, TOC,TS
Total PCBs,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Pyrene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Benzo(k)Fluoranthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Fluoranthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Phenanthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Chrysene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Benzo(b)Fluoranthene,	SPMD,Mussels	TAT,TVS	T, TOC,TS
Others:			
Mercury	Ultra-Clean	T,D	T,TVS
Fecals	Methods	T	
Tributyltin	SAM	TAT	
Total Suspended Solids	Mussels SAM	0.45	PD

T = Total Concentration; D = Dissolved Concentration; = TOC Total Organic Carbon; TS = Total Sulfides; TVS = Total Volatile Solids; TAT = Total Time Averaged Concentration; PD = Phi Size Distribution; 0.45 = 0.45μ Filter

CSO contaminant concentrations were obtained by sampling five of the largest CSOs that discharge along the Duwamish. They were Brandon, Connecticut, King, Hanford, and Chelan Regulators. The sampling program was designed to test whether chemical concentrations changed over the duration of the discharge event (first flush effects), whether they varied between CSO outfalls, or whether they varied across the depth of the CSO pipe. Additionally, previous testing results were available for the Denny Way CSO site regarding chemical analysis, solids settling, and how metals partition to suspended solids.

Sampling QA/QC

Collection of water samples was started before the County had developed the analytical techniques to remove the saline matrix from the samples. The new technique lowered detection levels an order of magnitude below what was previously achievable. While this was good, it also proved to be problem. The lower detection limit increased the degree to which sample contamination could be observed. Standard QA/QC revealed significant field blank contamination had occurred in most samples for lead, copper, and zinc. The sample values were subsequently blank corrected using the limited information that was available.

Model Configuration

John Hamrick from TetraTech Inc. configured the model with assistance from King County staff.

Elliott and Duwamish Boundary Conditions

At the model boundaries, Elliott Bay is forced by a phased harmonic tidal series. The Harmonics and phasing were determined from water-level time-series data taken near Fourmile Rock and Alki Point. The phasing accounts for the time it takes the tidal wave to travel across the boundary length. At the upstream I-405 Green River boundary tidal effects are minor. Conditions at the Green River boundary were driven by fresh water flows obtained from the US Geological Survey (USGS) flow station at Auburn. Daily average flows were used.

Chemical data gathered from the field monitoring program at the Tukwila and Duwamish Head field stations were used at the Green River and Elliott Bay boundaries respectively for model calibration. Boundary conditions for the one-year and ten-year simulations were generated from a simple stochastic model developed from observed data. Correlation analysis of the Tukwila data indicated a significant relation between zinc, lead, and copper, but less so with nickel. No significant correlation existed for arsenic and cadmium. Analysis of the Duwamish Head data at the 20-m depth indicated a correlation between cadmium, copper, and arsenic. Analysis of all data indicated no significant correlation between river flow, rainfall, or CSOs. Data generation for both boundaries entailed generating a primary constituent with the same statistical properties as the observed field data, and then generating the other constituents from the primary, maintaining the observed correlation.

CSOs

Currently 13 King County CSOs discharge into Elliott Bay and the Duwamish Estuary. Hydrographs used for the calibration are from flow data recorded over the 1996–'97 year. Hydrographs for the ten-year runs were generated from the county's basin run-off and hydraulic routing models and historical rainfall data from a recent ten year period. The rainfall periods were matched to the historical Green River flow data at the Auburn station.

Analysis of the chemical data from the CSO monitoring program indicated that there were was no significant change in concentrations over the duration of the discharge. Concentrations appeared to vary over the depth of the pipe, and there were subtle differences in concentrations between a few of the CSOs and a few of the metals of concern. As a result, average concentrations for each of the five CSOs for each of the COPCs were used in the model. For the remaining seven CSOs that were not monitored,

concentrations were estimated from one of the five CSOs based on similar basin characteristics; see Appendix A for grouping and concentrations.

Other Sources

The actual number of other sources that discharge into the Duwamish Estuary and Elliott Bay are unknown. However, an estimate of total run-off into the estuary was modeled using the County's basin run-off model. The county currently maintains a basin run-off and conveyance model for the Westpoint and Renton treatment plants to estimate sewer flow through the pipe network. The model is calibrated to observed flows in the sewer conveyance system and includes effects from stormwater inflows generated by rainfall. The portion of the storm water from impervious-area flow that does not enter the sewer system was considered to drain into the storm system. Run-off flow was routed along basin drainage lines and discharged into the Duwamish and Elliott Bay as another source. Forty-one discharge hydrographs of storm water were generated from the run-off model.

Chemical input for the other source loads was obtained from historical stormwater data. Since the intent of the modeling was to estimate chemical loads from other sources, stormwater chemical concentrations were adjusted until model predictions were comparable to observed data. Exact concentrations were not required, only reasonable estimates were needed. Use of the stormwater data does not imply all loads from "other sources" are solely from stormwater drains. The review did not provide stormwater chemical data for some of the COPCs. In these instances, CSO data was used. Appendix A summarizes initial chemical conditions for other sources.

Sediments and Suspended Solids

Sediment concentrations from Elliott Bay and the Duwamish were obtained from the DOE SedQual database. This data set was supplemented with data collected from the WQA. Sediment particle size for the bay and estuary was obtained from GeoSea Consulting, which gathered the data for the Elliott Bay/Duwamish Restoration Program. This data was also supplemented with particle information collected by Science Applications International Corp. (1991) for the US Army Corps of Engineers (ACOE) dredging at the turning basin. Very little sediment chemistry and particle data information is available for the Green River section of the model. A small amount of particle size information was obtained from an in-field assessment of percent fines at four locations by county technicians, as well as anecdotal evidence from the USGS. The data was collated to initialize sediment concentrations and particle distribution within all model cells. Multiple points within a single cell were averaged into a single value. Cells with no data points were interpolated from neighboring cells.

Review of all the sediment and CSO sampling data indicated that the sediments could be divided into three general classes, fine sand to course silt, silts, and fine silt to clay. Solids concentrations at the Green River boundary for fine sand/course silt class were generated using the Corps of Engineers Suspended Solids Loading Equation (ACOE 1981). Concentrations for the finer solids were generated from a similar regression equation using Total Suspended Solids (TSS) field data collected for the WQA and USGS Auburn flow data. The field-monitoring program provided suspended solids concentrations for CSOs. Solids concentrations for other sources were obtained from existing stormwater studies.

Chemical Properties

Chemical partition values for the metals As, Cu, Cd, Pb, Ni, and Zn were estimated from field data using the following equation (Thomann 1987),

Equation 1

$$P = \frac{c_T - c_d}{c_d m}$$

Where: P is the partition coefficient

c_T is total chemical concentration

c_d is dissolved chemical concentration

m is total suspended solids concentration

An average partition coefficient was computed for each sample site and the sample averages were combined to compute a single partition coefficient. A constant partition coefficient was used for all chemicals. However, sample averages indicated that partitioning varied along the length of the estuary. An attempt was made to develop a regression equation to explain the observed relation between salinity and the partition coefficient, but none of the equations proved to be statistically significant. Chemical partitioning for the organic compounds, tributyltin, and mercury were obtained from literature references (Hamrick 1998).

Chemical decay rates for the organic compounds were obtained from literature references (Howard et al. 1991). Minimum rates were used for both water and sediment columns. A zero decay rate was used for unlisted chemicals. Partition and decay values are summarized in Table 2.

Table 2. COPC chemical properties.

Chemical of Concern	Decay (1/sec)	Partition Coefficient (l/mg)	
		Water	Sediments
Arsenic	None	0.02	0.005
Cadmium	None	0.018	0.004
Copper	None	0.11	0.025
Lead	None	4.4	0.4
Nickel	None	0.042	0.01
Zinc	None	0.082	0.02
Tributyltin	None	1.0e-3	Same
1,4-Dichlorobenzene	None	8.1e-5	Same
4- Methylphenol,	None	2.4e-6	Same
Bis(2-ethylhexyl)Phthalate	3.5e-7	4.8e-3	Same
Fluoranthene	3.1e-6	9.8e-3	Same
Phenanthrene	7.7e-6	8.4e-4	Same
Total PCBs	None	2.2e-3	Same
Pyrene	9.4e-5	3.4e-3	Same
Benzo(k)Fluoranthene	3.9e-7	3.0e-1	Same
Chrysene	1.5e-5	2.1e-2	Same
Benzo(b)Fluoranthene	2.7e-7	1.5e-1	Same
Mercury	None	4.4e-4	Same

Model Calibration

John Hamrick calibrated the hydrodynamic portion of the EFDC computer model and sent the calibrated model to King County staff for the mass calibration of the COPCs.

Sediments

The first constituent to calibrate was the suspended solids component. The only parameter adjustment was the suspended solids settling velocity. While the model requires specifying a critical sediment stress at which resuspension occurs, no field measurements were made to estimate a critical stress value. Instead literature references were used as suggested by Hamrick (1.6×10^{-4} [m/sec]^2 non-cohesive and 1×10^{-4} [m/sec]^2 cohesive). At first, two sediment types were selected, fine sand and silt. Sediment samples from ACOE (SAIC 1991) pre-dredging studies indicated that most of the solids deposited in the turning basin are fine to medium sands. A third solids class was added with a settling velocity similar to clays and flocculated material due to the fact that too much sediment was settling out. The solids in the CSOs were also divided into silts and clays, with the same settling velocities as those used in the river.

Settling velocities and solids loads at the Green River boundary were adjusted for all three classes until an optimum fit between observed and predicted solids concentrations was reached. The best fit occurred with a suspended solids distribution at the Green River boundary of 78% fine sands, 15% silts, and 7% clays, and 100% clay at the Elliott Bay boundary. Suspended solids from CSOs and other sources were negligible compared to that from Green River. Final settling velocities for each class was 0.01 m/sec for the fine sands, 0.004 m/sec for silts, and 1×10^{-6} m/sec for the clays. The final calibration graph for TSS at the Brandon site are shown in Figures 3 and 4, for the surface and bottom levels.
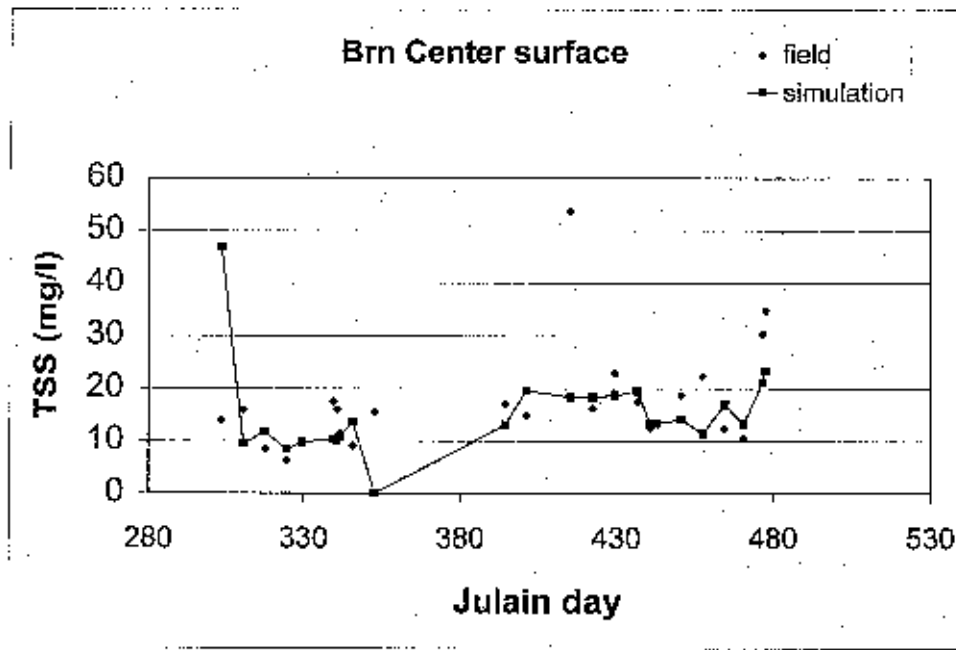
Figure 3. Calibrated total suspended sediment concentration one meter below the surface.
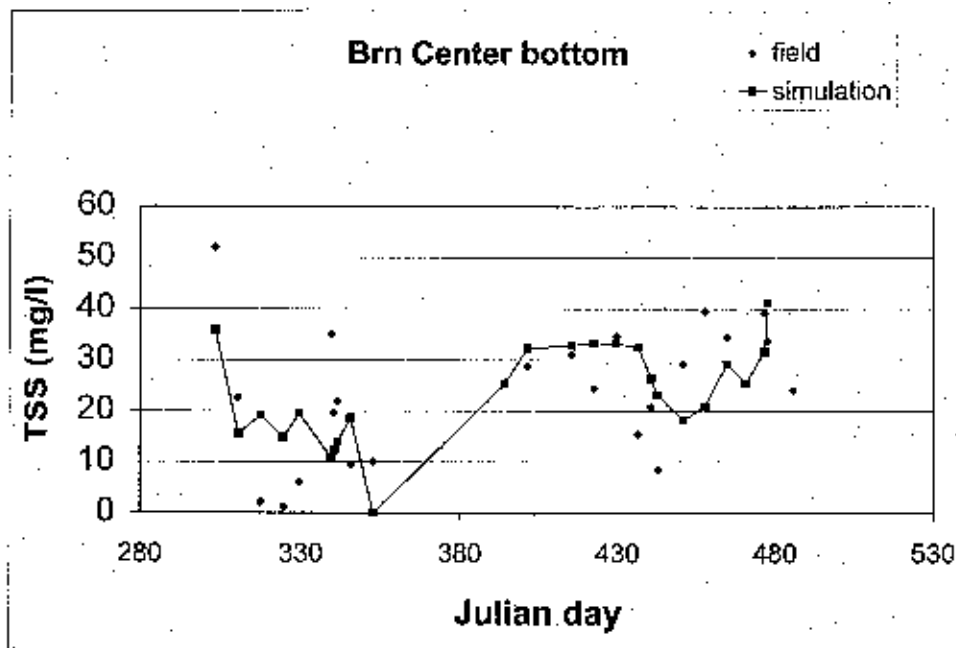

Figure 4. Calibrated total suspended sediment concentration one meter above the bottom.

Metals

Metals were calibrated after the sediment calibration was completed. Calibration entailed adjusting load inputs from "other sources" until simulated metals concentrations were comparable to observed data. Metals loading from CSOs were not adjusted, since it was assumed that inputs from CSOs had been adequately defined in the sampling program.

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The model simulated the transport of metals in two phases, dissolved and particulate. Division between the two phases was defined by the partition coefficients given in Table 2 and the suspended solids as given by equation 1. It was assumed that the partition coefficients remained constant in both space and time. Given that the partition coefficient does not vary, and that the suspended solids field has been defined, differences in simulated and observed metals concentrations were ascribed to other source loads. The model simulates chemical loads using a hydrograph and chemical concentration time series. It multiplies the flow rate by the chemical concentration to give a chemical flux into the cell. To adjust the load that discharges into the cell, either the flow rate or the chemical concentrations can be manipulated. For the EFDC model it is easier to manipulate the chemical concentration time series rather than the hydrograph.
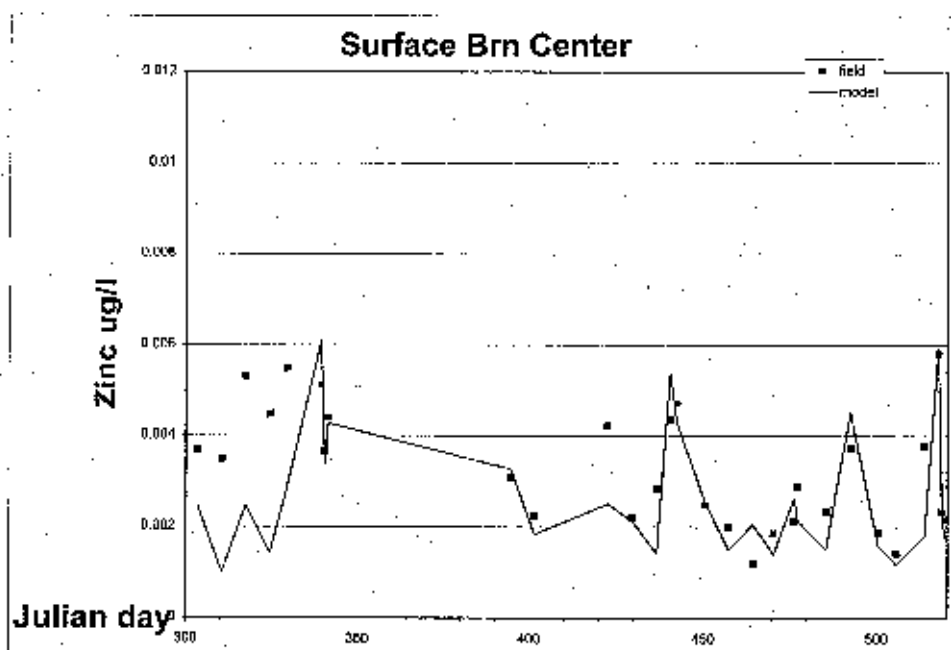

Figure 5. Calibrated total zinc water concentrations one meter below the surface.

Calibration was carried out in a series of steps, each step refined the previous steps. The first steps were to match the general fit of model predictions to field observations. After the general fit was completed, the next steps refined model predictions at specific points in the observed time series. This entailed adjusting either the existing hydrographs, chemical time series, or adding a separate hydrograph and chemical time series as needed to match observed field data. Final calibration graphs for zinc at the Brandon site, one meter below the surface and one meter above the bottom are shown in Figures 5 and 6.
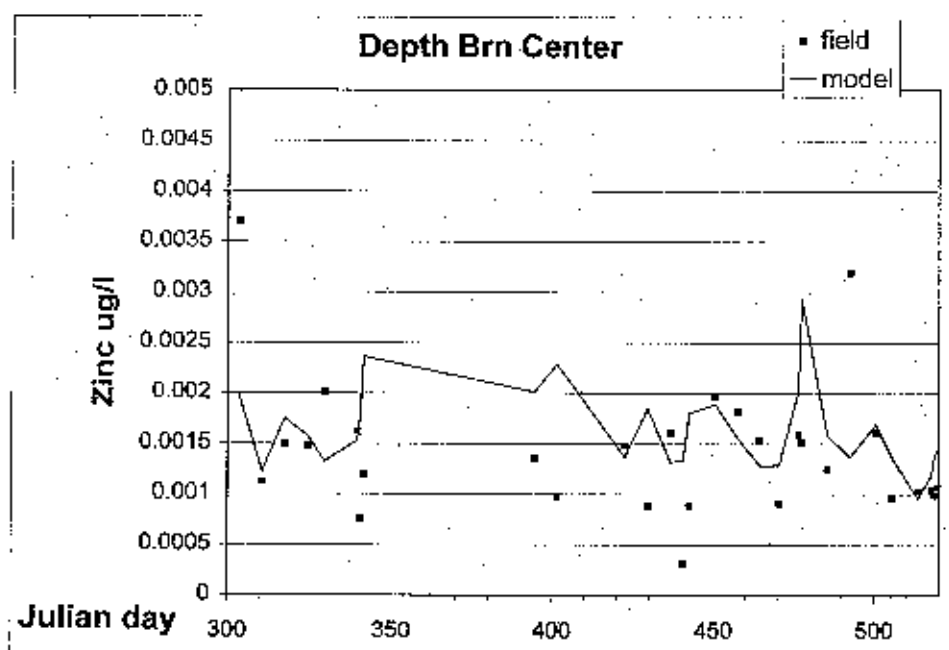
Figure 6. Calibrated total zinc water concentrations one meter above the bottom.

Organic Compounds

The organic compounds were calibrated using sample data from mussels and SPMDs. The concentrations in the mussel tissue were converted to average concentrations in the water column that would approximately result in the sampled tissue concentration. Concentrations in the SPMDs were placed in the water for two weeks. The concentrations of contaminants in the SPMDs were converted to average water column concentrations that would result in the SPMD values. Data from the model was saved and averaged over the time periods that the mussels and the SPMDs were in the water.

Calibration Results

Final chemical concentrations for other source inputs are listed in Table 3. Final CSO concentrations are shown in Table 4.

Results of Modeling

The calibrated model was run for one-year and ten-year periods. The one-year period simulation looked at differences between CSOs and other sources in the water column and estimated differences in the sediment column. Chemical concentrations were saved every hour for every model cell. The ten-year period was run to verify or correct the one-year sediment estimates. The ten-year run was necessary because of the generally slow response of sediments to loading changes, and it was not known if current sediment concentrations were in equilibrium with the existing environment.

Model results for the one-year simulations with and without CSOs have not been evaluated at the time of writing this paper. Therefore, a comparison of the impacts between CSOs and other sources has not been done at this time. However, the calibration process did reveal some information about the models' ability to simulate the highly stratified conditions in the estuary, and the relative influence of boundary sources to observed metals concentrations. The model is able to give a reasonable simulation of contaminant transport through the estuary, and the results are being used to perform a risk assessment on the impact of CSOs relative to other sources.

Table 3. Final chemical concentrations for other sources.

Metals							Organics	
Other Sources					Eastside Inputs			
Source (mg/L)	Arsenic	Cadmium	Copper	Lead	Nickel	Zinc	TBT	Phenanthrene
Pre-Julian day 400	4.64	0.95	22	22.8	0.0	134	0.0	1.44
Post-Julian day 400	3.9	0.95	22	10.8	0.0	70.8	0.0	1.44
				Westside Inputs				
Pre-Julian day 400	4.64	0.9	22	26.2	7.1	156.8	0.0	1.44
Post-Julian day 400	3.9	0.9	22	20.9	7.1	114	0.0	1.44

Organics								
Source (µg/L)	Chrysene	Fluoranthene	Pyrene	1,4-Dichloro benzene	4-Methyl phenol	Benzo(b) fluoranthene	Benzo(k) fluoranthene	Total PCB
Eastside Inputs	0.06	0.43	3.59	0.15	2.32	0.015	0.0005	0.0
Westside Inputs	0.06	0.43	3.59	0.15	2.32	0.015	0.0005	0.0

Table 4. Arithmetic mean chemical concentrations for CSOs.

Metals (µg/L)							
Arsenic	Cadmium	Copper	Lead	Nickel	Zinc	Mercury (ng/l)	TBT (ug/l)
2.87	0.51	32.78	30.68	8.24	130.17	26.95	0.0

Organic (µg/L)								
Total PCB	Chrysene	Fluoranthene	Phenanthrene	Pyrene	1,4-Dichloro benzene	4-Methyl phenol	Benzo(b) fluoranthene	Benzo(k) fluoranthene
0.0	0.242	0.43	0.439	0.363	0.382	5.62	0.239	0.208

Summary

The Duwamish Estuary and Elliott Bay is a highly stratified flow system where CSOs and other sources tend to discharge into the system. The EFDC model adequately simulated the stratified flow and transport of metals and organic compounds through the estuary and into the bay, maintaining observed chemical differences between the fresh water lens and the saline wedge. Assessment of the calibration process indicates that the most influential source of arsenic and cadimum is from Puget Sound. The Green River is the primary source for nickel.

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